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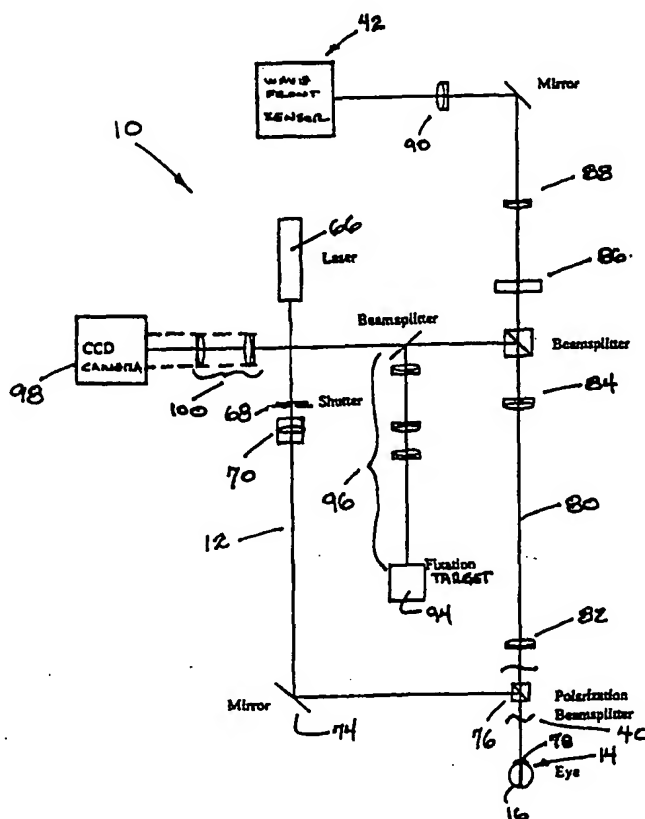
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**(54) Title:** APPARATUS AND METHOD FOR MEASURING VISION DEFECTS OF A HUMAN EYE

**(57) Abstract**

Optical characteristics of optical systems, such as the eye (14), are measured including vision defects of the eye using a collimated beam (12) from a diode laser (66) focused onto the anterior surface (22) of the cornea (24) of the eye for providing a finite source (16) of secondary radiation on the retina (18) of the eye, the image of which is close to a desired diffraction limited spot. The secondary radiation is reflected back from the retina (18) as a reflected wavefront of radiation that passes through the eye and is directed onto a wavefront analyzer (42) where distortions associated with the reflected wavefront are measured. By focusing on the cornea (24) through a long focal length lens (70) and thus converging the beam through a small angle (13), as opposed to typically focusing a collimated light onto the retina (18), the need for lenses or lens combinations, and the time required to adjust such to accommodate the differing vision of each patient is eliminated.



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## APPARATUS AND METHOD FOR MEASURING VISION DEFECTS OF A HUMAN EYE

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### Related Application

This Application is related to Provisional Application having Serial No. 60/097,086, filed on August 19, 1998 for "Apparatus and Method for Measuring Vision Defects of a Human Eye" commonly owned with the instant application.

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### Background of Invention

#### Field of Invention

The invention relates generally to optical aberration measurements and correction, and in particular to projection techniques in the objective measurement and correction of the human eye using a wavefront sensor.

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#### Description of Background Art

There has been and continues to be a need to provide a person with improved visual acuity. Remodeling of the cornea using refractive laser surgery or intra-corneal implants, adding synthetic lenses using intra-ocular lens implants or precision ground contact lenses or eye glasses provide known solutions. Further, it is known to correct vision astigmatically by surgical modification of myopic or hyperopic astigmatism through laser keratoplasty, keratomileusis or photorefractive keratectomy. Laser sources are used to erode or ablate surfaces of the eye, typically reshaping the cornea. Prior to and during such surgery, precise measurements must be made to determine required surgical corrections.

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The imprecise measurement technique of placing lenses of known refractive power anterior to the cornea and asking a patient which lens or lens combination provides the clearest vision has been improved with the use of autorefractometers, as described in U.S. Patent No. 5,258,791 to Penny et al., or with the use of wavefront sensors as described by Liang et al. in "Objective Measurement of Wave Aberrations of the Human Eye with the Use of a Hartmann-Shack Wave-Front Sensor," Journal of the Optical Society of America, Vol. 1, No. 7, July 1994, p.p 1949-1957, by way of examples. Penny '791 discloses the use of autorefractometer measurements for determining the appropriate corneal surface reshaping to provide

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emmetropia, a condition of a normal eye when parallel rays are focused exactly on the retina and vision is optimum. Spatially resolved refraction data, in combination with measured existing surface contour of the anterior surface of the eye, enable a calculation of a detailed spatially resolved new contour which provides corrected vision. It would be an improvement in this art if such vision correction could be made without the need for this contour data, and further without the need for feedback from the patient regarding an appropriate lens. Liang et al. disclose the use of a Hartmann-Shack wavefront sensor to measure ocular aberrations by measuring the wavefront emerging from the eye by retinal reflection of a focused laser light spot on the retina's fovea. A parallel beam of laser light passes through beam splitters and a lens pair which brings the beam to a focus point on the retina by the optics of the eye. Possible myopia or hyperopia of the tested eye is corrected by movement of a lens within the lens pair. The focused light on the fovea is then assumed to be diffusely reflected and acts as a point source located on the retina. The reflected light passes through the eye and forms a distorted wavefront in front of the eye that results from the ocular aberrations. The aberrated wavefront is then directed to the wavefront sensor.

A point source of radiation on the retina would be ideal for such measurements. However, when the perfect eye receives a collimated beam of light, the best possible image on the retina is a diffraction limited spot. As illustrated by way of example, with Penny et al. and Liang et al., discussed above, and typical for those of skill in the art, parallel or collimated beams are used with the optics of the eye being measured to achieve this diffraction limited spot for such objective measurements. To do so requires that a setup for each patient include a corrective lens or lens combination and adjustments thereto for accommodating that patient's specific visual acuity. Providing a corrective or lens combination, as well as setting up for their use becomes cumbersome, time consuming, and requires additional expense. Eliminating the need for such corrective optics is desirable and eliminates a variable within optical measurement systems that typically include many variables. Further, there is a need for providing optical characteristics of an eye without requiring feedback from the patient. By way of example, the patient may be a wild or domestic animal, living or dead.

### Summary of Invention

In view of the foregoing background, it is therefore an object of the present invention to provide a refraction measurement system that easily accommodates the measurement of vision characteristics of the eye, even in the presence of finite refractive errors. It is another object to improve upon the time required for a patient to be in a fixed position during examination, while at the same time providing a useful source of light on the retina of the eye to be measured regardless of the characteristics of the eye of that patient or other patients to be examined. It is further an object to measure such characteristics without requiring patient or operator feedback.

These and other objects, advantages and features of the present invention are provided by a method aspect of the invention for measuring optical characteristics of an optical system including the focusing of an optical beam proximate an anterior surface of the optical system for placing a finite source of secondary radiation on a focal surface of the optical system, which secondary radiation is emitted from the focal surface as a reflected wavefront of radiation that passes through the optical system, projecting the reflected wavefront onto a wavefront analyzer, and measuring characteristics of the optical system associated with the reflected wavefront. In a preferred embodiment, the method includes measuring defects of the eye which includes the steps of focusing an optical beam onto an anterior surface of the eye for providing a finite source of secondary radiation on the retina of the eye, which secondary radiation is emitted from the retina as a reflected wavefront of radiation that passes through the eye; directing the reflected wavefront onto a wavefront analyzer; and measuring distortions associated with the reflected wavefront. A preferred embodiment of the invention includes the step of focusing the projected optical beam on the anterior surface of the cornea.

An apparatus for effectively performing such measurements includes focusing means for focusing an optical beam onto an anterior surface of the optical system or eye for providing a finite secondary radiation source on the focal surface, or retina of the eye, which finite secondary radiation source is emitted from the retina as a reflected wavefront of radiation that passes through the eye, directing means for directing the reflected wavefront onto a wavefront analyzer, and a wavefront

analyzer for measuring distortions associated with the reflected wavefront. In one preferred embodiment of the present invention, a laser beam is focused onto the surface of the cornea with a long focal length lens which converges the beam through a small angle for passing through the iris of the eye and providing a finite secondary radiation source on the retina of the eye, which finite secondary radiation source is emitted from the retina through the optics of the eye as the wavefront to be measured.

### Brief Description of Drawings

A preferred embodiment of the invention as well as alternate embodiments are described by way of example with reference to the accompanying drawings in which:

FIG. 1 is a diagrammatic illustration of an apparatus for measuring visual defects of an eye, according to the present invention;

FIG. 2 is a diagrammatic illustration of a eye to be measured by the apparatus of the present invention;

FIGS. 3A and 3B are diagrammatic illustrations of an ideal eye with perfect vision and an aberrated ideal eye, respectively;

FIG. 4 is a diagrammatic illustration of an eye being measure with collimated light focused on the retina to a diffraction limited spot; and

FIG. 5 is a partial perspective view of a pinhole imaging plate and detector plane of a wavefront sensor used in a preferred embodiment of the present invention.

### Detailed Description of Preferred Embodiments

The present invention will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

A preferred embodiment of a measurement apparatus 10 of the present invention is herein initially described with reference to the schematic diagram of FIG. 1. A projected beam 12 of optical radiation is directed into an eye 14 to be measured, so that a small area or measurable spot 16 is formed as a secondary radiation source in the foveal region of the retina 18 as illuminated with reference to FIG. 2. Specifically, the beam 12 is focused through a small angle 13 onto an anterior surface 20 of the eye 14, and in a preferred embodiment of the present invention, focused on an anterior corneal surface 22 of the cornea 24 for further projection through the iris 26 and lens 28 and onto the retina 18.

By way of further background, consider an "ideal" eye 14i with ideal vision, as illustrated with reference to FIG. 3A. The ideal eye 14i, having the ideal cornea 24i and ideal lens 28i will focus a collimated beam of light, illustrated with arrows 30 to a point 32, as the secondary radiation source, on the ideal retina 18i. This point 32 would then be a point source of light which would be diffusely reflected back through the optics of the ideal eye 14i as a sequence of plane waves 34. In actual fact, even an eye having perfect vision, as illustrated by way of example with reference to FIG. 4, will produce a diffraction limited illuminated area or spot 36, as the secondary radiation source, on the retina of the eye, under the best possible circumstances. In a typical eye, as illustrated with reference to FIG. 4, such a spot 36 is even larger, where most of the blurring will be due to finite aberrations found in typical eyes. By way of further example, in an aberrated eye 14a, if the point source 32 could be realized, distorted wavefronts 38 result as illustrated with reference to FIG. 3B. Having to deal with a series of distorted wavefronts 38 resulting from aberrations, and further dealing with a blurring of such distorted wavefronts 38 resulting from diffraction effects and the finite aberrations of the eye, results in a spot 36 source of light rather than a point 32 source. Such provides one of the challenges in measuring the visual defects of an eye.

It is typical in the art of eye measurements to form a collimated beam and attempt to focus the collimated beam onto the retina, using lenses and lens combinations with the optics of the eye to produce the smallest possible spot 36, as earlier described with reference to FIG. 4. Lenses and focusing techniques typically take valuable time and include multiple attempts to focus a spot on the retina using

various lenses and lens combinations to accommodate each unique vision of each patient being measured. With the present invention, and the understanding that most of the blurring results from the curvature of the cornea, the present invention eliminates the need to find lenses or lens combinations to minimize the size of the spot on the retina that is used as the secondary source of radiation.

With reference again to the embodiment described in FIGS. 1 and 2, the optical wavefronts 40 scattered from the retina 18 are transferred by a series of optical elements, which will be described in further detail later in this section, to a wavefront sensor 42, which wavefront sensor divides each incident wavefront into a group of "wavelets", referred to herein with numeral 50, using an opaque plate 44 having a planar array of apertures 46 as illustrated with reference to FIG. 5. Further, the wavefront sensor 42 records the position 48 at which each wavelet 50 passing through the aperture 46 strikes a detector plane 54 such as a charged coupled device (CCD) herein provided as one preferred embodiment, which plane is held a fixed small distance 56 behind the plate 44. The transverse displacement 58 of each wavelet 50 at the CCD detector plane 54 from a collimated light reference position 60 is then used to calculate a wavefront slope at each position of the apertures 46 within the planar aperture array. Alternate methods exist for using partial derivative data resulting from the measurements of the slope to calculate the wavefront 40. One acceptable approach is that used by Liang et al. in the aforementioned paper where the wavefront is closely approximated using Zernike polynomials.

At each position 48, a spot 62 typically extending beyond the light measurement area of one CCD element 64 is produced. As earlier discussed, blurring and a large diffraction limited spot make it difficult to make measurements. Thus, reducing blurring improves measurement at the detector plane 54.

With reference again to FIG. 1, in one preferred embodiment of the present invention, the apparatus 10 includes the projected beam 12 of linearly polarized light (S-component) emitted from a diode laser 66 (670 nm, 3 mW by way of example), which beam of light passes through an electro-mechanical shutter 68, which controls the duration of light exposure on the eye 14 of the patient, and in particular, the exposure of the retina 18 of the eye 14 illustrated with reference again to FIG. 2. It



is expected that alternate sources of light, for example, non-coherent and non-polarized, as well as alternate light transmitting techniques will come to the mind of those skilled in the art without deviating from the teaching of the present invention.

As herein described, the use of coherent light from a laser and polarization

5 techniques are presently preferred. When the shutter 68 is open, the projected beam 12, collimated light from the diode laser 66, is directed by a long focal length lens 70 for focusing on the anterior surface 22 of the cornea 24 of the eye 14, as illustrated with reference yet again to FIG. 2, passing through the pupil 72 and lens 28 of the eye 14, and onto the retina 18 as the small measurable spot 16. In an  
10 alternate embodiment, lens 70 comprises a zoom lens for varying the focus and moving the focus location as desired. By focusing on the cornea 24, the measurement is minimally dependent on the curvature of the cornea. However, other locations proximate the corneal surface are acceptable.

While diffraction and various aberrations are present, the present invention  
15 avoids the aberration effects from the cornea which typically dominate. The lens 28 of the eye 14 contributes a relatively small aberration effect when compared to that of the cornea 24. Further, and with regard to the selection of lens 70, selecting a lens with a short focal length would provide a large angle 13, a well focused point 78 on the surface of the cornea 24, and less aberration effects from the cornea .

20 However, a large angle 13 results in an undesirably larger retinal spot 16. The small angle 13 herein described provides a larger focus point 78 on the cornea 24 but the more desirable smaller spot 16 on the retina 18. The spot 16 will depend on the wavelength and starting point size and focal length of the lens 70 selected. In preferred embodiments of the present invention, lenses of approximate one half  
25 meter are selected for the lens 70. A 100 mm lens 70 has been effectively used.

In one preferred embodiment herein described, a mirror 74 and polarization beam splitter 76 direct the projected beam 12 to a focus 78 on the anterior surface 20 of the cornea 24. The projected beam 12, focused on the anterior surface 22 of the cornea 24, provides the measurable spot 16 as a light source (about 1.5  
30 milliradians in visual space, by way of example) on the retina 18 of the eye 14 being measured, as illustrated with reference again to FIG. 2. Such a spot 16 provides an acceptable substitute for a diffraction limited spot typically sought.

By way of one preferred example of use, a method for measuring vision characteristics of the eye 14 includes directing the beam 12 through the long focal length lens 70 for providing the small angle 13, as illustrated with reference again to FIG. 2, about an optical path for passing the beam 12 through the pupil 72 of the eye 14. The beam 12 is first focused at a fixed location 78, without the eye or patient in place. All measuring equipment, the apparatus 10, is arranged without the patient in place and a convenient time prior to measuring. Then, the patient is positioned such that the anterior surface of the eye 14 of a patient is located at the fixed location 78 which in a preferred embodiment is the anterior surface of the cornea. This places a finite source of secondary radiation, the spot 16, as herein described, on the retina 18 of the eye 14, which provides light emitted from the retina 18 and through the pupil 72 as a reflected wavefront, the wavefront 38, described with reference to FIG. 3B. This wavefront 38 is directed onto the wavefront analyzer 42 for measurement.

In a preferred embodiment, the laser power reaching the eye is physically limited to a maximum of 7 $\mu$ W. In measurements on human eyes using the apparatus 10, a laser pulse duration of 700 ms was used so that the total energy entering the eye would not exceed 4.9  $\mu$ J. For comparison, according to the ANSI standard for direct "intrabeam" viewing, the maximum permissible exposure to a laser at the wavelength used is 530  $\mu$ J. Thus, the probing laser energies effectively used in the present invention are two orders of magnitude below an "eye-safe" limit.

With reference again to FIG. 2, the light diffusely reflected by the retina 18 produces the wavefront 40, a distorted wavefront at the pupil plane due to the eye's aberrations. Diffuse reflection makes the returning light from the retina depolarized, containing not only an S-component but also a P-component of polarization light. The polarization beam splitter 76 in front of the eye 14 will only let the P-component pass through it and downstream to the wavefront sensor 42. The S-component is essentially totally reflected towards the diode laser 66. Because the light reflected by corneal surfaces preserves the polarization of the incoming beam (S-polarized), the corneal reflection is reflected by the beam splitter 76, and is thus rejected from the path 80 heading toward the wavefront sensor 42. The P-component of the aberrated wavefront 40 at the subject's pupil plane is then recreated by the

combination of lens 82 and lens 84, at a trial lens plane 86 indicated as "Trial Lens" in FIG. 2. In one preferred embodiment, the diameter and the aperture of the lens 82 and lens 84 are 40 mm and 120 mm, respectively. The combination of lens 82 and lens 84 form an afocal image system with the eye's pupil 72 (the object plane) at the focal plane of the lens 82, and the image plane, trial lens 86, at the focal plane of the lens 84. Similarly, lens 88 and lens 90 also form an afocal image system with the possible trial lens 86 at the focal plane of the lens 88 and the lens combination at the image plane at the focal plane of the lens 90. The focal plane of the lens 90 is located at the plate 44 of the wavefront sensor 42, earlier described with reference to FIG. 5. In a preferred embodiment, Lens 4 has a diameter of 30 mm and a focal length of 80 mm. Lens 5 has a diameter of 40 mm and a focal length of 120 mm. With the apparatus 10, measured wavefront slopes leaving the eye 14 are recreated at the aperture plane 44, and magnified by a factor of 1.5. Magnification of the wavefront 40 at the detector plane 54 reduces the wavefront slopes by the same degree. This extends the dynamic range of eye aberrations over which the device can measure.

By way of further explanation about the trial lens location or plane 86, because the wavefront 40 leaving the eye 14 is recreated at this location 86 with unity magnification, a trial lens of known refractive power inserted at this point should exactly compensate for a prescribed refractive error. For example, a perfect five diopter spherical lens placed at this location should remove five diopters of spherical curvature from an incident wavefront, without altering other aberrations that may exist in the wavefront. The capability of inserting trial lenses at this location 86 extends the dynamic measurement range of the apparatus 10, without affecting wavefront analyzing capability.

In a preferred embodiment, and with reference again to FIG. 5, the aperture array 46 of the wavefront sensor 42 samples the incident wavefront 40 which forms focus spots 62 on the detector plane 54. This is repeated at the detector plane 54 for each aperture within the array 46. As a result, a localized direction of the wavefront 40 is determined for each of a plurality of wavelets 50 within the array. By way of example, the use of lenslets 92 (as an alternate embodiment of apertures 46 alone), with a focal length of 87 mm and a dimension of 0.768 mm, forms an arial

image of the retinal light source (the spot 16 described earlier with reference to FIG. 2) on the detector plane 54. If a plane wave, corresponding to an aberration-free eye, were measured, the lenslet 92 array would produce a regular array of focused spots on the image sensor. When the real eye 14 is measured, the wave aberration in the eye will displace the focus spot 62, described earlier with reference to FIG. 5, of each lenslet 92 from the reference position 60 to the measured position 50 in proportion to the local slopes of the wavefront 40. The wavefront sensor 42 measures the local wavefront slopes at an array of sampling locations across the pupil 72, from which the wavefront 40 itself can be reconstructed.

As illustrated again with reference to FIG. 1, in an alternate embodiment of the present inventive methods, a fixation target 94 may be used to insure that the patient is looking along the optical axis of the apparatus 10. The patient is asked to fixate on the target 94 located at the focal plane of a lens 96. By linearly moving the optics combination 96 of the fixation target 94, it is possible to provide the eye's spherical correction, and hence to make the fixation target 94 clearly visible to the subject. In one preferred use, the image of the fixation target 94 is intentionally under-corrected for each patient to ensure that the measured eye 14 is focused at infinity. By way of example, the fixation target consists of a dark cross-hair and a number of concentric circles on a white background that is back-illuminated by a tungsten lamp. The patient is asked to look at the center of the cross-hair. The position of the eye 14 in reference to the optical axis is recorded by CCD camera 98. This CCD camera 98 is conjugate, in effect coupled, to the eye's pupil 72 through a second lens combination 100, preferably mounted on the camera, and the lenses 82, 84. In one method of the present invention, the camera 98 is used to view the eye 14 for aligning the eye within the path of the beam 12 for assuring that the beam passes through the pupil 72. The camera 98 is also useful in an alternate embodiment of the present invention, for viewing the size of the spot 16 formed on the retina 18 as the user changes the focus point 78 through various anterior surface locations in obtaining an optimum size of the spot 16.

By way of further example of effective uses of the present invention, the earlier described Zernike coefficients of an eye, taken collectively, can be used as discriminating as fingerprints or DNA. The Zernike coefficients for a person might be

used for identification of that person for permitting access to a confidential area, allowing funds to be distributed through an ATM, and the like. Further, the present invention allows eye measurements for a passive subject, such as in the examination of a corpse or sedated animal. The present invention is operable with human eyes, as herein described, as well as those of an animal, bird, or fish eyes, and in particular, non-biological focusing optical systems such as those found in cameras. The present invention is useful in developing optimized aspheric systems, where an aspheric element need to be designed last by observing and producing a single custom aspheric element that corrects the system. By way of example, the aspheric system may be designed on paper except for the correcting element, which would be developed experimentally using the present invention as herein described. The design of afocal systems such as a telescope, a searchlight, or a projector which require an added corrective focus element will benefit from the present invention.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and alternate embodiments are intended to be included within the scope of the appended claims.

**That Which Is Claimed Is:**

- 1                   **1.**     A method for measuring vision defects of an eye, the method  
2     comprising the steps of:  
3                   focusing an optical beam proximate an anterior surface of the eye for  
4     placing a finite source of secondary radiation on the retina of the eye, which  
5     secondary radiation is emitted from the retina as a reflected wavefront of radiation  
6     that passes through the eye;  
7                   projecting the reflected wavefront onto a wavefront analyzer; and  
8                   measuring distortions associated with the reflected wavefront.
- 1                   **2.**     The method according to Claim 1, wherein the optical beam  
2     focusing step includes the step of focusing the optical beam on the anterior surface  
3     of the cornea.
- 1                   **3.**     The method according to Claim 1, wherein the optical beam  
2     comprises a collimated laser beam.
- 1                   **4.**     The method according to Claim 1, further comprising the steps  
2     of:  
3                   generating a linearly polarized, collimated beam of light; and  
4                   positioning a long focal length lens for directing the collimated beam of  
5     light through the long focal length lens, and wherein the focusing step includes the  
6     step of converging the collimated light through a small angle to a focal point on the  
7     anterior surface of the eye.
- 1                   **5.**     The method according to Claim 4, wherein the long focal length  
2     lens has a focal length between 0.5 and 5.0 meters in length.
- 1                   **6.**     The method according to Claim 4, further comprising the step  
2     controlling an amount of optical beam energy delivered to the eye.

1           **7.**     The method according to Claim 1, wherein the distortion  
2     measuring step comprises the step of comparing the reflected wavefront received by  
3     the wavefront analyzer to a desirable wavefront received by the wavefront analyzer.

1           **8.**     The method according to Claim 1, wherein the distortion  
2     measuring step comprises the step of determining an optical path difference  
3     between a plane wave and the wavefront emanating from the retina of the eye.

1           **9.**     The method according to Claim 8, wherein the optical path  
2     difference results from a Zernike reconstruction of the wavefront.

1           **10.**    The method according to Claim 1, wherein the distortion  
2     measuring step comprises the steps of:  
3                 positioning an opaque plate having an aperture therein for transmitting  
4     a portion of the emitted wavefront therethrough;  
5                 placing a light-sensitive material downstream of and in spaced relation  
6     to the opaque plate for receiving the portion of the reflected wavefront projected as a  
7     finite image onto a first position of the light-sensitive material;  
8                 projecting the reflected wavefront onto the plate for placing a first finite  
9     image onto the light-sensitive material;  
10                projecting a desirable wavefront onto the plate for placing a second  
11     finite image at a second location on the light-sensitive material; and  
12                measuring a difference between the first position and the second  
13     position.

1           **11.**    The method according to Claim 10, wherein the aperture  
2     comprises an aperture array and wherein the light-sensitive material comprises a  
3     CCD array.

1           **12.**    The method according to Claim 11, wherein the aperture array  
2     comprises a lens carried within each aperture for focusing light passing through the  
3     aperture onto the CCD array.

1           **13.** The method according to Claim 1, further comprising the step of  
2 converting the measured distortions to an optical correction based on a deviation of  
3 the reflected wavefront from a desirable wavefront.

1           **14.** The method according to Claim 13, wherein the desirable  
2 wavefront comprises a planar wavefront.

1           **15.** The method according to Claim 14, wherein the polarizing step  
2 comprises the steps of:

3                 providing a beam splitter;  
4                 passing the reflected wavefront having an S-component and a P-  
5 component polarization light through the beam splitter; and  
6                 splitting the reflected wavefront by directing the P-component to the  
7 wavefront analyzer and the S-component therefrom.

1           **16.** The method according to Claim 1, further comprising the step of  
2 polarizing the optical beam.

1           **17.** The method according to Claim 1, further comprising the steps  
2 of:

3                 positioning a fixation target for viewing;  
4                 focusing the eye on the fixation target for assuring that a patient whose  
5 eye is being measured is looking along a preferred direction.

1           **18.** The method according to Claim 17, further comprising the step  
2 of adjusting the fixation target for ensuring that the measured eye is focused at  
3 infinity.

1           **19.** The method according to Claim 1, further comprising the steps  
2 of:  
3                 viewing the pupil of the eye through a camera focused on the eye; and



4 aligning the center of the eye along a beam path of the optical beam  
5 for confirming passage of the beam through the pupil of the eye.

1 **20.** A method for measuring vision characteristics of an eye, the  
2 method comprising the steps of:

3 projecting an optical beam through a sufficiently small angle about an  
4 optical path for passing the beam through the pupil of the eye and providing a finite  
5 spot on the retina of the eye;

6 focusing the optical beam proximate an anterior surface of the eye for  
7 placing a finite source of secondary radiation on the retina of the eye, which  
8 secondary radiation provides light emitted from the retina and through the pupil as a  
9 reflected wavefront of radiation; and

10 directing the reflected wavefront onto a wavefront analyzer for  
11 measuring distortions associated with the reflected wavefront.

1 **21.** The method according to Claim 20, wherein the optical beam  
2 focusing step includes the step of focusing the optical beam on the anterior surface  
3 of the cornea.

1 **22.** The method according to Claim 20, wherein the optical beam  
2 comprises a laser beam.

1 **23.** The method according to Claim 20, further comprising the steps  
2 of:

3 generating a linearly polarized optical beam; and

4 positioning a long focal length lens for directing the optical beam  
5 therethrough, and wherein the focusing step includes the step of directing the optical  
6 beam through the long focal length lens for providing the small angle in which to  
7 focus the optical beam.

1 **24.** The method according to Claim 23, wherein the long focal  
2 length lens has a focal length of at least one half meter in length.

1                   **25.**    The method according to Claim 20, further comprising the steps  
2 of:  
3                   providing a shutter within a beam path of the optical beam; and  
4                   controlling an amount of optical beam energy delivered to the eye by  
5 operating the shutter from a closed position to an open position.

1                   **26.**    The method according to Claim 20, further comprising the step  
2 of measuring an optical path difference between a desirable wavefront and the  
3 wavefront emanating from the retina of the eye.

1                   **27.**    The method according to Claim 26, wherein the measuring step  
2 comprises the steps of:  
3                   positioning an opaque plate having an aperture array therein for  
4 transmitting a plurality of emitted wavelets of the emitted wavefront therethrough;  
5 and  
6                   receiving finite images of the plurality of emitted wavelets on a light  
7 sensitive material downstream of and in spaced relation to the opaque plate.

1                   **28.**    The method according to Claim 27, further comprising the steps  
2 of:  
3                   determining positions for each of the plurality of emitted wavelet finite  
4 images;  
5                   projecting the desirable wavefront onto the plate for placing a plurality  
6 of reference wavelets onto the light sensitive material;  
7                   determining positions for each of the plurality of reference wavelet  
8 finite images; and  
9                   measuring a displacement between finite images, respectively, for the  
10 emitted wavelets and reference wavelets.

1           **29.**   The method according to Claim 28, further comprising the step  
2 of converting the displacement to an optical correction based on a difference  
3 between the reflected wavefront and the desirable wavefront.

1           **30.**   The method according to Claim 29, wherein the desirable  
2 wavefront comprises a planar wavefront.

1           **31.**   The method according to Claim 30, further comprising the steps  
2 of:  
3               polarizing the optical beam;  
4               passing the reflected wavefront through a beam splitter, wherein an S-  
5 component and a P-component of the polarized optical beam pass through the  
6 beam splitter; and  
7               splitting the reflected wavefront by directing the P-component to the  
8 wavefront analyzer and the S-component therefrom.

1           **32.**   A method for measuring vision characteristics of an eye, the  
2 method comprising the steps of:  
3               directing an optical beam through a long focal length lens for providing  
4 a sufficiently small angle about an optical path for passing the optical beam through  
5 the pupil of the eye;  
6               focusing the optical beam at a fixed location;  
7               positioning an anterior surface of the eye of a patient at the fixed  
8 location for placing a finite source of secondary radiation on the retina of the eye,  
9 which secondary radiation provides light emitted from the retina and through the  
10 pupil as a reflected wavefront of radiation; and  
11              directing the reflected wavefront onto a wavefront analyzer for  
12 measuring the reflected wavefront.

1           **33.**   The method according to Claim 32, wherein the anterior surface  
2 comprises the anterior surface of the cornea.

1                   **34.**   The method according to Claim 32, wherein the long focal  
2   length lens has a focal length of at least one half meter in length.

1                   **35.**   The method according to Claim 32, further comprising the steps  
2   of:  
3                   providing a shutter within a beam path of the optical beam; and  
4                   controlling an amount of optical beam energy delivered to the eye by  
5   operating the shutter from a closed position to an open position.

1                   **36.**   The method according to Claim 32, further comprising the step  
2   of measuring an optical path difference between a desirable wavefront and the  
3   wavefront emanating from the retina of the eye.

1                   **37.**   The method according to Claim 32, further comprising the steps  
2   of:  
3                   polarizing the optical beam;  
4                   passing the reflected wavefront through a beam splitter, wherein an S-  
5   component and a P-component of the polarized optical beam pass through the  
6   beam splitter; and  
7                   splitting the reflected wavefront by directing the P-component to the  
8   wavefront analyzer and the S-component therefrom.

1                   **38.**   The method according to Claim 32, wherein the positioning step  
2   comprises the steps of:  
3                   viewing the pupil of the eye through a camera focused on the eye; and  
4                   aligning the center of the eye along a beam path of the optical beam  
5   for confirming passage of the beam through the pupil of the eye.

1                   **39.**   A method for measuring vision characteristics of an eye  
2   comprising focusing an optical beam proximate an anterior surface of the eye for  
3   providing a finite source of secondary radiation on the retina of the eye, which

4 secondary radiation is emitted from the retina as a reflected wavefront of radiation  
5 that passes through the eye.

1 40. The method according to Claim 39, wherein the optical beam  
2 focusing includes focusing the optical beam on the anterior surface of the cornea.

1 41. The method according to Claim 39, further comprising projecting  
2 the reflected wavefront onto a wavefront analyzer and measuring differences  
3 between the reflected wavefront and a desirable wavefront.

1 42. The method according to Claim 39, further comprising  
2 generating a linearly polarized, collimated beam of light and positioning a long focal  
3 length lens for directing the collimated beam of light through the long focal length  
4 lens, wherein the focusing includes converging the collimated light through a small  
5 angle to a focal point on the anterior surface of the eye.

1 43. ... The method according to Claim 42, wherein the linearly....  
2 polarized collimated beam comprises a laser beam.

1 44. The method according to Claim 39, further comprising viewing  
2 the size of the finite secondary radiation source on the retina, and varying anterior  
3 surface focus locations for selecting a desired size of the source.

1 45. A method for measuring optical characteristics of an optical  
2 system, the method comprising the steps of:  
3 focusing an optical beam proximate an anterior surface of the optical  
4 system for placing a finite source of secondary radiation on a focal surface of the  
5 optical system, which secondary radiation is emitted from the focal surface as a  
6 reflected wavefront of radiation that passes through the optical system;  
7 projecting the reflected wavefront onto a wavefront analyzer; and  
8 measuring characteristics of the optical system associated with the  
9 reflected wavefront.

1                   **46.**    The method according to Claim 45, wherein the optical system  
2   comprises a human eye, and wherein the focal surface comprises the retina of the  
3   eye.

1                   **47.**    The method according to Claim 45, wherein the distortion  
2   measuring step comprises the step of comparing the reflected wavefront received by  
3   the wavefront analyzer to a desirable wavefront received by the wavefront analyzer.

1                   **48.**    The method according to Claim 45, wherein the distortion  
2   measuring step comprises the step of determining an optical path difference  
3   between a plane wave and the wavefront emanating from the optical system.

1                   **49.**    The method according to Claim 48, wherein the optical path  
2   difference results from a Zernike reconstruction of the wavefront.

1                   **50.**    The method according to Claim 45, wherein the distortion  
2   measuring step comprises the steps of:  
3                   positioning an opaque plate having an aperture therein for transmitting  
4   a portion of the emitted wavefront therethrough;  
5                   placing a light sensitive material downstream of and in spaced relation  
6   to the opaque plate for receiving the portion of the reflected wavefront projected as a  
7   finite image onto a first position of the light sensitive material;  
8                   projecting the reflected wavefront onto the plate for placing a first finite  
9   image onto the light sensitive material;  
10                  projecting a desirable wavefront onto the plate for placing a second  
11   finite image at a second location on the light sensitive material; and  
12                  measuring a difference between the first position and the second  
13   position.

1                   **51.**    The method according to Claim 50, wherein the aperture  
2 comprises an aperture array and wherein the light sensitive material comprises a  
3 CCD array.

1                   **52.**    The method according to Claim 45, further comprising the step  
2 of converting the measured distortions to an optical correction based on a deviation  
3 of the reflected wavefront from a desirable wavefront.

1                   **53.**    The method according to Claim 45, further comprising the steps  
2 of:  
3                   viewing the focal surface through a camera; and  
4                   selecting a desired size of the finite source of secondary radiation.

1                   **54.**    An apparatus for measuring vision characteristics of an optical  
2 system, the apparatus comprising:  
3                   focusing means for focusing an optical beam proximate an anterior  
4 surface of the optical system for providing a finite source of secondary radiation on a  
5 focal surface, which secondary radiation is emitted from the focal surface as a  
6 reflected wavefront of radiation that passes through the optical system;  
7                   directing means for directing the reflected wavefront onto a wavefront  
8 analyzer; and  
9                   a wavefront analyzer for measuring distortions associated with the  
10 reflected wavefront.

1                   **55.**    The apparatus according to Claim 54, wherein the focusing  
2 means comprises a long focal length lens for converging the optical beam through a  
3 small angle and focusing the optical beam on the anterior surface.

1                   **56.**    The apparatus according to Claim 55, wherein the long focal  
2 length lens has a focal length of at least one half meter in length.

1                   **57.**    The apparatus according to Claim 54, wherein the focusing  
2   means comprises a zoom lens for converging the optical beam through a small  
3   angle and varying the focusing of the optical beam onto various anterior surfaces.

1                   **58.**    The apparatus according to Claim 54, further comprising a laser  
2   for providing the optical beam.

1                   **59.**    The apparatus according to Claim 54, further comprising the a  
2   shutter operable from a closed position to an open position for controlling an amount  
3   of optical beam energy delivered to the optical system.

1                   **60.**    The apparatus according to Claim 54, wherein the wavefront  
2   analyzer comprises:  
3                    an opaque plate having an aperture therein for transmitting a portion of  
4   the emitted wavefront therethrough; and  
5                    a light-sensitive material downstream of and in spaced relation to the  
6   opaque plate for receiving the portion of the reflected wavefront projected as a finite  
7   image thereon.

1                   **61.**    The apparatus according to Claim 60, wherein the aperture  
2   comprises an aperture array and wherein the light-sensitive material comprises a  
3   CCD array.

1                   **62.**    The apparatus according to Claim 61, further comprising a lens  
2   carried within each of the plurality of apertures of the aperture array.

1                   **63.**    The apparatus according to Claim 54, further comprising  
2   polarizing means for polarizing the optical beam.

1                   **64.**    The apparatus according to Claim 63, further comprising a  
2   polarization beam splitter for reflecting an S-component of the reflected wavefront



3 and for transmitting a P-component of the reflected wavefront as a polarized  
4 wavefront therethrough.

1           **65.** The apparatus according to Claim 54, further comprising a  
2 camera positioned for viewing the focal surface.

1           **66.** An apparatus for measuring vision characteristics of an eye, the  
2 apparatus comprising:  
3           a laser for providing an optical beam;  
4           focusing means for focusing the optical beam on an anterior surface of  
5 the eye for providing a finite source of secondary radiation on the retina of the eye,  
6 which secondary radiation is emitted from the retina as a reflected wavefront of  
7 radiation that passes outward from the eye;  
8           polarizing means placed within a path of the optical beam for  
9 transmitting a polarized wavefront therethrough; and  
10          a wavefront analyzer receiving the polarized wavefront for measuring  
11 distortions associated therewith.

1           **67.** The apparatus according to Claim 66, wherein the focusing  
2 means comprises a long focal length lens for converging the optical beam through a  
3 small angle and focusing the optical beam on the anterior surface.

1           **68.** The apparatus according to Claim 67, wherein the long focal  
2 length lens has a focal length of approximately one half meter in length.

1           **69.** The apparatus according to Claim 66, further comprising the a  
2 shutter operable from a closed position to an open position for controlling an amount  
3 of optical beam energy delivered to the eye.

1           **70.** The apparatus according to Claim 66, wherein the wavefront  
2 analyzer comprises:

3                   an opaque plate having an aperture therein for transmitting a portion of  
4   the emitted wavefront therethrough; and  
5                   a light-sensitive material downstream of and in spaced relation to the  
6   opaque plate for receiving the portion of the reflected wavefront projected as a finite  
7   image thereon.

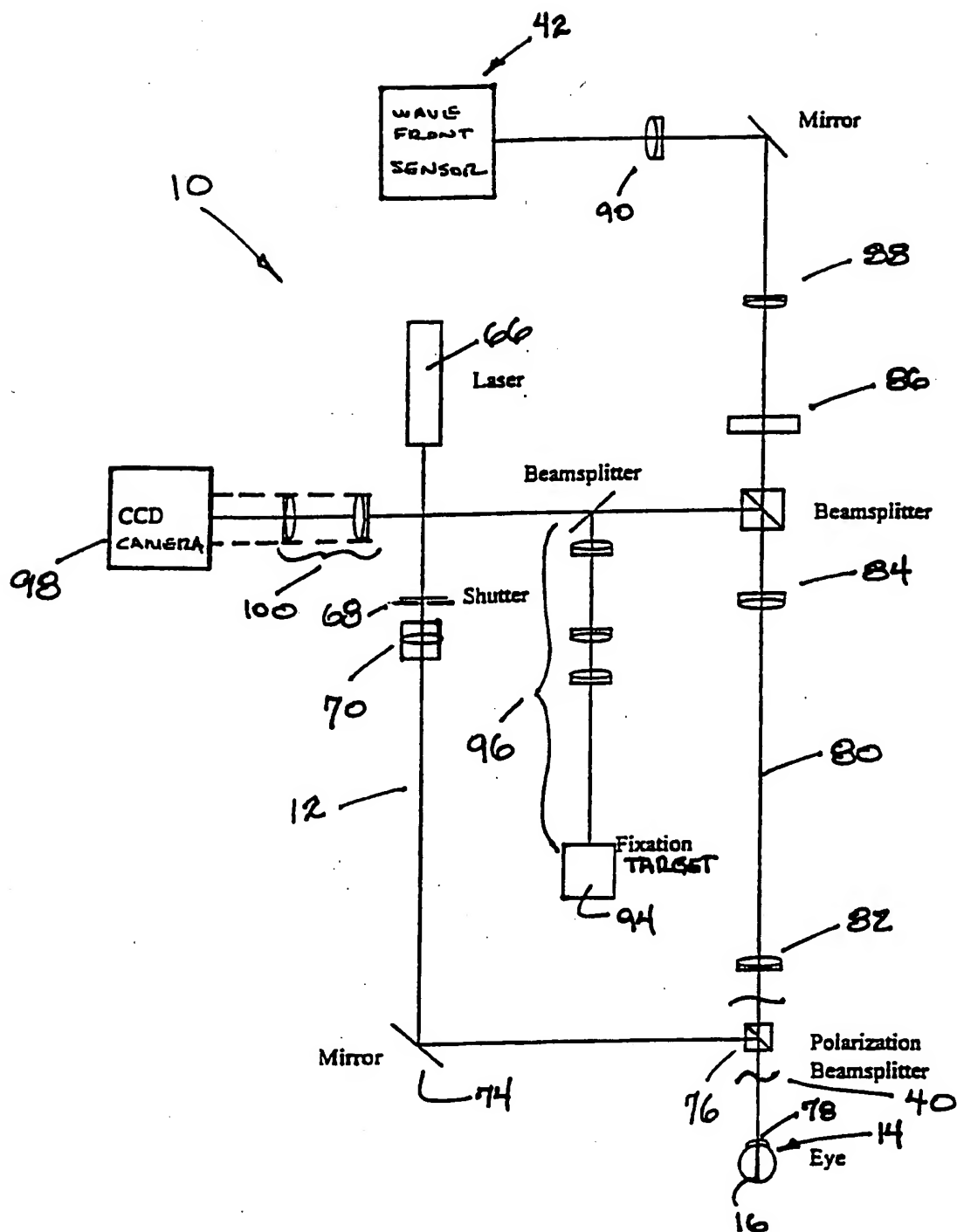
1                   **71.**   The apparatus according to Claim 70, wherein the aperture  
2   comprises an aperture array and wherein the light-sensitive material comprises a  
3   CCD array.

1                   **72.**   The apparatus according to Claim 71, further comprising a lens  
2   carried within each aperture of the aperture array.

1                   **73.**   The apparatus according to Claim 66, further comprising a  
2   fixation target for viewing by a patient whose eye is being measured, the fixation  
3   target assuring that a patient whose eye is being measured is looking along a  
4   preferred direction.

1                   **74.**   The apparatus according to Claim 66, further comprising a  
2   camera positioned for viewing the focal surface.

1/3

FIG. 1

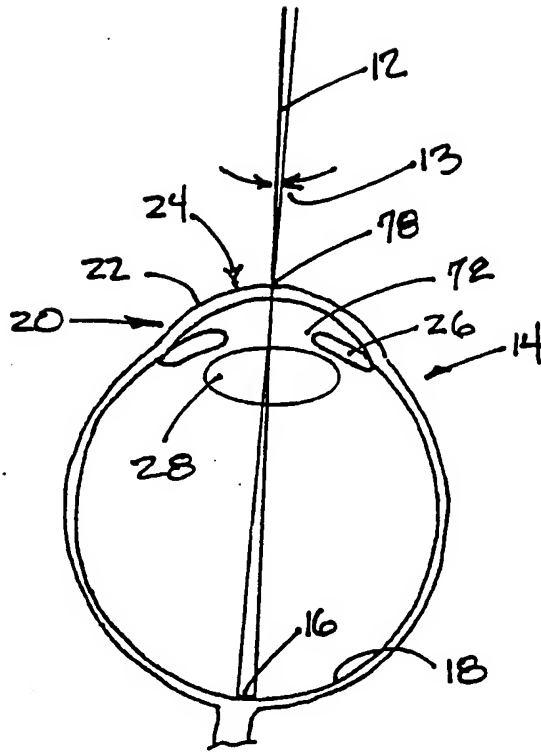


FIG. 2

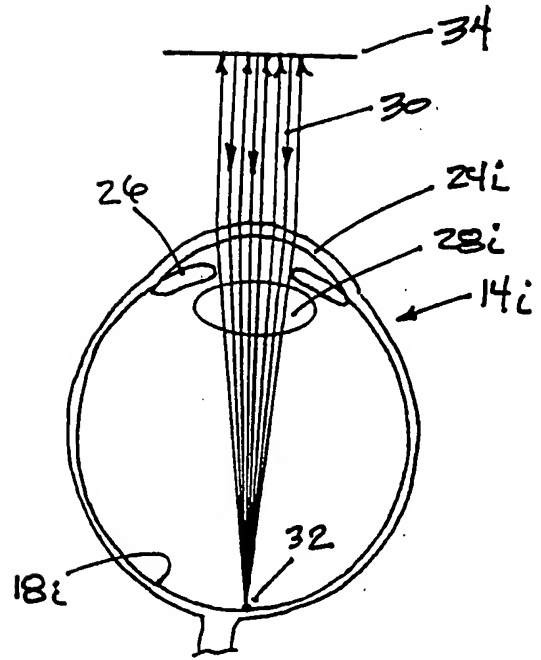


FIG. 3A

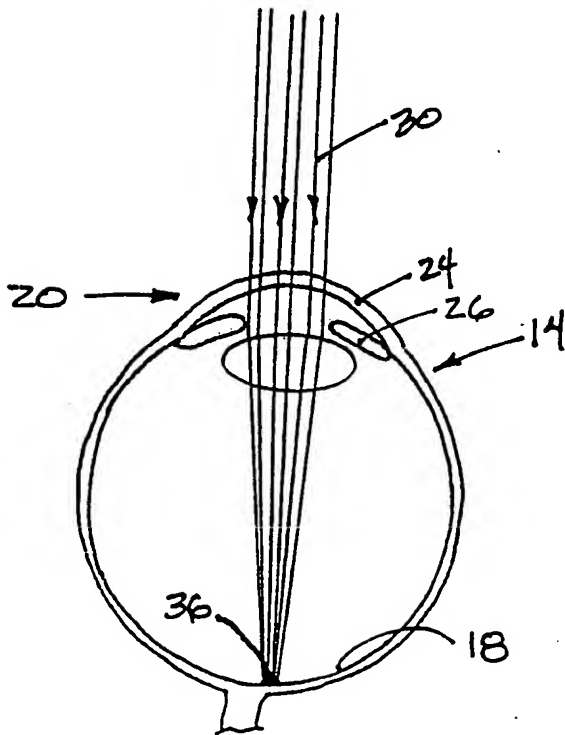


FIG. 4

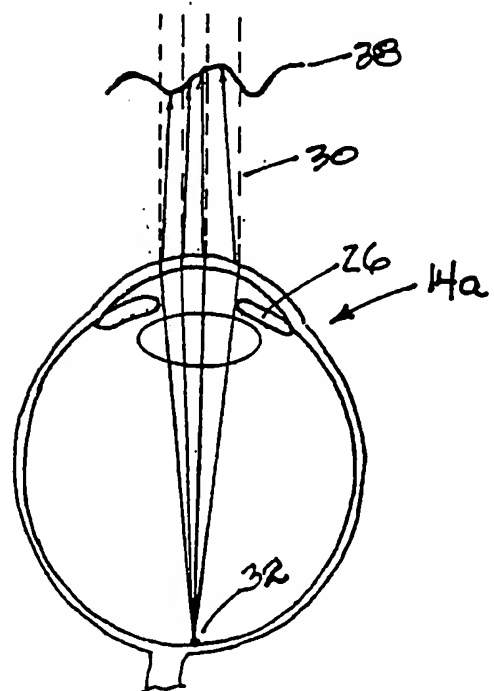


FIG. 3B

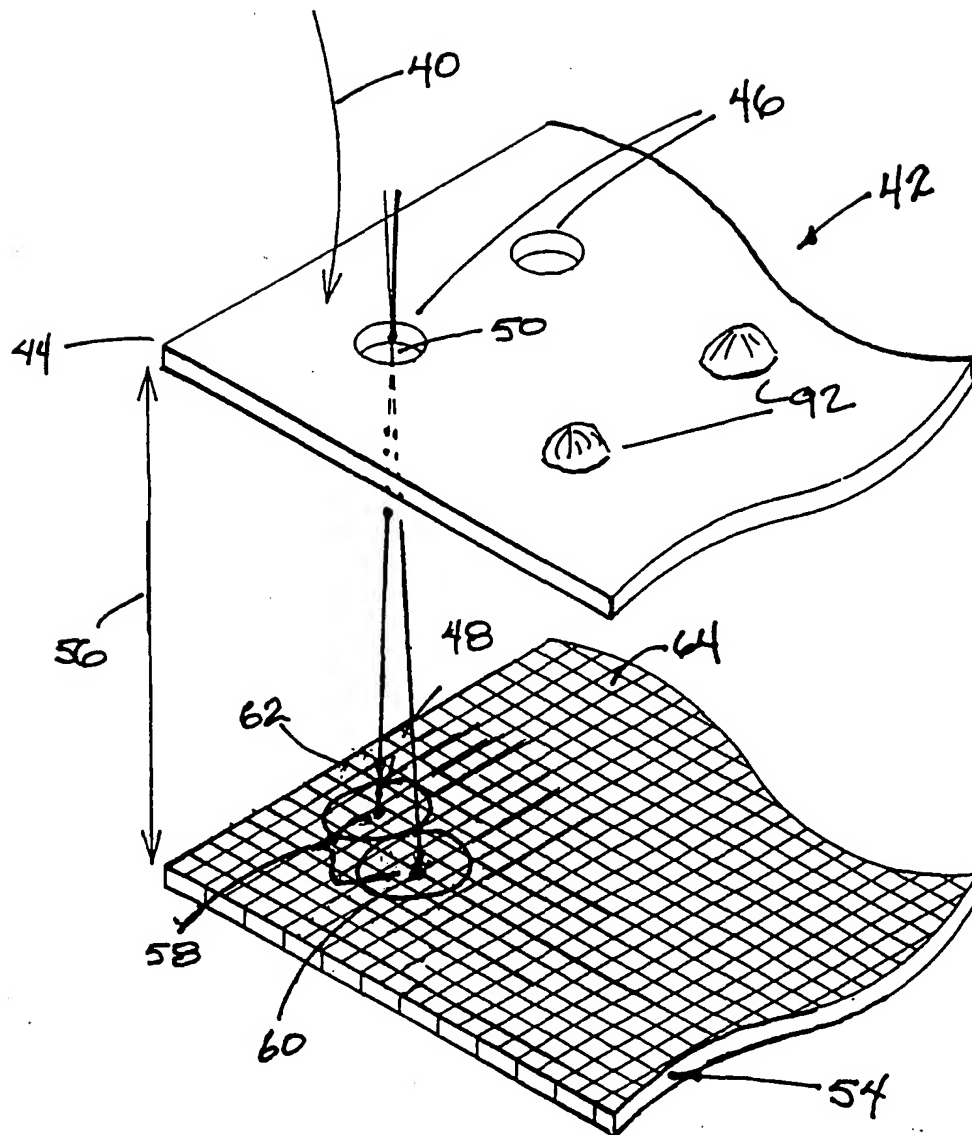


FIG. 5

# INTERNATIONAL SEARCH REPORT

Int :ional Application No  
PCT/US 99/08709

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A61B3/103

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 98 27863 A (UNIVERSITY OF ROCHESTER) 2 July 1998 (1998-07-02)	1, 20, 32, 39, 45, 54, 66
A	page 6, line 2 - page 9, line 9 figures 1, 2	3, 4, 6-17, 22, 23, 25-31, 35-37, 42, 43, 46-52, 58-64, 69-72
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

### \* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "O" document referring to an oral disclosure, use, exhibition or other means
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- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search

4 August 1999

Date of mailing of the international search report

11/08/1999

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# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US 99/08709

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 757 463 A (KOHAYAKAWA) 26 May 1998 (1998-05-26)  column 2, line 1 - line 50 column 4, line 13 - column 5, line 12 figures 1,6	1,20,32, 39,45, 54,66
A		2,4,21, 23,33, 55,67
A	DE 42 22 395 A (AMTECH) 13 January 1994 (1994-01-13)  column 4, line 10 - column 6, line 45 figure 1	1,3,4, 15-20, 22,31, 32, 37-39, 42,45, 54,61, 63-65, 71,73,74
A	EP 0 697 611 A (CARL ZEISS) 21 February 1996 (1996-02-21)  column 5, line 33 - line 52	1,2,4,5, 21,23, 32,33, 40,55, 66,67
A	US 3 880 501 A (MUNNERLYN) 29 April 1975 (1975-04-29) column 2, line 4 - column 4, line 27 figure 2	15,31,37
A	DREHER ET AL.: "Active optical depth resolution improvement of the laser tomographic scanner" APPLIED OPTICS, vol. 28, no. 4, 15 February 1989 (1989-02-15), pages 804-808, XP002064185 us page 804, right-hand column, line 1 - left-hand column, line 23	57

# INTERNATIONAL SEARCH REPORT

Int. Application No  
PCT/US 99/08709

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9827863 A	02-07-1998	US 5777719 A AU 5806298 A	07-07-1998 17-07-1998
US 5757463 A	26-05-1998	JP 7016207 A	20-01-1995
DE 4222395 A	13-01-1994	NONE	
EP 697611 A	21-02-1996	US 5493109 A JP 8066421 A	20-02-1996 12-03-1996
US 3880501 A	29-04-1975	NONE	